Integrated Silicon Microheating Elements using Silicon-on-Plastic Drop-In Functionality

Laurie E. Locascio and Michael Gaitan
Analytical Chemistry Division and Semiconductor Electronics Divsion
National Institute of Standards & Technology, Gaithersburg, MD 20899
Email: laurie.locascio@nist.gov, gaitan@nist.gov

Keywords: microheaters, silicon elements, plastic microchannels, flow sensor, integration

Abstract

Resistive IC-based thin film microheating elements of polysilicon encapsulated in glass are coupled with polymeric microfluid channels. These microheating elements have several advantages over other resistive heating elements including high thermal isolation and good chemical compatibility due to the fact that they are encapsulated in glass. The microheating elements have been aligned and permanently bonded to plastic imprinted microfluid channels. The first demonstration of the utility of integrated microheating elements is their use as integrated microflow sensors.

1. Introduction

MicroTAS systems can be broken down into active and passive elements in a manner directly analogous to electronic systems. Microchannels as fluid conduits can be characterized as simple passive elements in a microTAS system while pumps, valves, and sensors can be classified as active components. One of the first demonstrations of the higher integration necessary for production of true lab-on-a-chip devices involved the fabrication of microchannels in a thin film process directly onto a silicon wafer containing active components [1]. Achieving integration in this manner is advantageous in that the entire system can be batch-fabricated. A disadvantage, however, is the relatively expensive real-estate on the silicon wafer supports passive elements and is not optimally utilized in this format.

We are taking a different approach to integration by designing systems that incorporate discrete silicon chips with fluid channels fabricated in plastics. The majority of our work to date has focused on the study and fabrication of microfluid channels in hard plastics using imprinting techniques. Initially, channels were prepared by imprinting at elevated temperature using a wire or silicon template as the imprinting tool. A major advantage of this technique, and similar approaches taken by ACLARA Biosciences [2] and Jenoptik [3], is cost. A disadvantage of the method is the lack of a simple path to active component integration. In this presentation, we will discuss methods to link microchannels fabricated in plastic to silicon chips to achieve higher levels of system integration. Silicon active elements will be added to the system using plastic as the main substrate material to support the micro-lab. Advantages of this approach are cost, system robustness and adaptability.

2. Experimental

Microheating elements were designed at NIST and fabricated in an ASIC foundry process through the MOSIS service [4]. The substrate silicon underlying the microheaters was etched in a top-side anisotropic etching process via through-holes using tetramethyl ammonium hydroxide (TMAH) at NIST [5]. After etching, the microheating elements were suspended structures as shown in Figure 1.

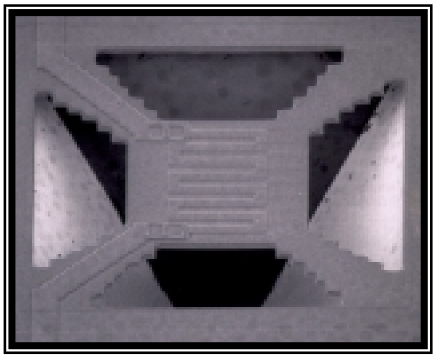


Figure 1 Microheating element fabricated in standard IC process as suspended trampoline structure. Dimensions of microheater are 150 by 150 μm.

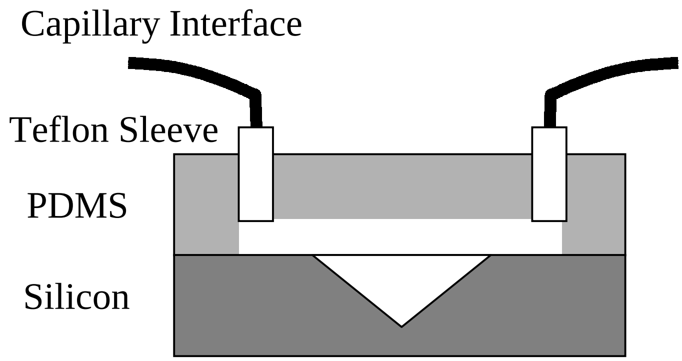


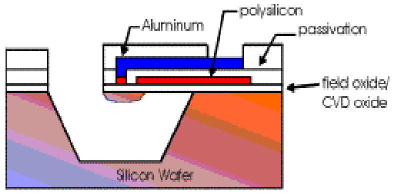
Figure 2 Side view of microheating element incorporated in plastic microfluid system.

A silicon template that was the raised image of the microchannel pattern was fabricated by standard photolithographic procedures [6]. Microchannels were formed in polydimethylsiloxane membranes by casting the uncured polymer over the silicon template and curing at room temperature for 24 h. Teflon sleeves were inserted into ferule tips and glued to the silicon template. The sleeves were cured into the polymer at either end of the microchannels forming a connection to external capillary tubing. After curing, the polymer membrane was removed from the silicon template and cut into small discrete plastic chips. The polymer microfluidic "chip" and the silicon microheating element chip were then placed in oxygen plasma for five seconds. Upon removal from the oxygen plasma chamber, the silicon and plastic chips were aligned and placed in contact forming a permanent bond [7]. When the bonding step was complete, capillary tubing was placed in the teflon sleeves and connected to a peristaltic pump or vacuum pump for flow control and modulation. The complete system is depicted in Figure 2.

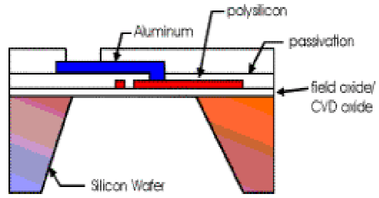
3. Results

Temperature control is critical for the control of chemical and biological reactions. The incorporation of active IC-based microheating elements into plastic microchannel systems is an improved method for achieving thermal control in lab-on-a-chip devices. The microheating elements are fabricated using a standard IC process with on-chip control electronics, and are composed of a polysilicon filament that is encapsulated entirely in glass. These devices have been extensively characterized and demonstrate temperature transition times of milliseconds [8] when cycling from ambient temperature to 1000 ^{o}C in air. High thermal isolation and fast response times are achieved by fabricating the microheating element as a thin suspended membrane structure rather than a resistive element (wire filaments) in contact with a substrate material. These characteristics are particularly important in applications that require rapid thermal cycling such as PCR. The microheating elements have been fabricated as individual devices and in arrays at NIST for other applications including their use as thermal emitters [9].

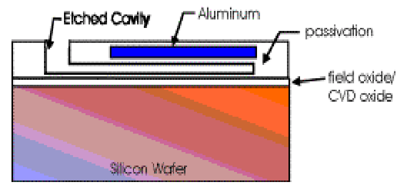
In the post-processing step, the thin film microheating elements are freed from contact with the bulk silicon substrate by a top-side anisotropic etching procedure shown in Figure 3A. A top-side etch requires that there are through holes in the microheater design exposing the underlying silicon. When the silicon is micromachined, the microheaters are suspended with four-point contact to the bulk silicon in a trampoline-type structure. This process leaves a trapezoidal pit below the element into which liquid can flow. Microheating elements can also be fabricated without a liquid-accessible volume below the element by



(A)



(B)



(C)

Figure 3 Micromachining methods for microheating elements: A. Top-side, B. back-side, and C. sacrificial etching.

back-side etching (Figure 3B) or sacrificial etching (Figure 3C). These designs are also being fabricated in our laboratory for testing in microfluid channels.

The microheating elements have been integrated into microfluid channels as described above. The microchannels were cast in polydimethylsiloxane and then aligned under a microscope and bonded to the IC chip containing microheating elements. A permanent seal between the polydimethylsiloxane membrane and the silicon chip could be developed by treating the membrane and silicon chip in an oxygen plasma. Solution was pumped through the microchannel through capillary tubing attached the microdevice. Pumping was accomplished using either a low volume syringe pump attached at the entrance of the microchannel or by vacuum attached to the channel exit.

The microheating elements were demonstrated as flow sensors in microfluid systems using vacuum pumping to control the flow rate through the microchannel. The principles of operation are similar to a hot wire anemometer measuring filament resistance change as a function of heat dissipation from the surface of the heating element. A constant current was applied to the microheating element while solution was pumped continuously through the microfluid channel. In this microheater design, solution passed over the element and also underneath the element through the etched holes in the silicon substrate. The resistance of the microheating element was measured as a function of pump pressure, corresponding to a change in the flow rate. The response of the device to change in pump pressure (flow rate) is plotted in Figure 4 with pressure corresponding to the vacuum pressure applied to the system. The change in resistance on the microheating element stabilized rapidly implying that the sensor could be used to measure flow continuously in the plastic microchannel system.

Rapid pulses of heat could be delivered to the microchannel device by increasing and decreasing the current through the microheating element. As the power dissipation of the

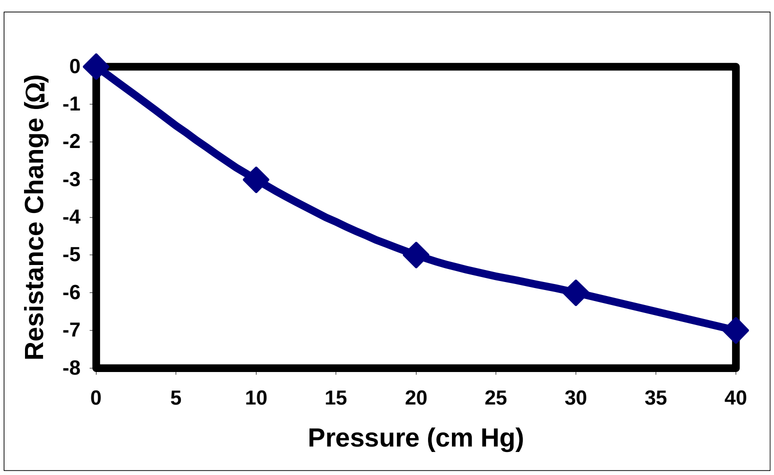


Figure 4 Response of the microheating element as a function of flow rate.

microheater was increased, bubbles were formed in the channel over the microheater occluding the channel completely. When the microheater was turned off, the bubble rapidly disappeared. Bubble formation did not appear to adversely affect the bond between the silicon and polymeric chips.

4. Conclusions

The microheating elements described in this paper have advantages over other resistive microheater designs in that they are thin film structures, and as such, demonstrate high thermal isolation. In other approaches to integrated resistive heating including wire filament deposition, thermal transfer to the surrounding medium is not as efficient due to the fact that the element is in direct contact with the bulk substrate. Lift-off, dissolution, or chemical reaction of metal filaments in solutions can cause fluctuations in their response. Glass encapsulation of the polysilicon filament in our devices leads to improved chemical resistance and compatibility.

In the current design of the element, the trapezoidal pit or well below the heater can serve as a microvial for chemical reaction. It has been previously shown that heat transfer to the etched well is high therefore chemical reaction inside the microvial should be promoted. The rapid response of these elements implies that they will be very useful for thermal cycling of chemical and biological reactions. Modeling of heat transfer from the device in liquids is currently under investigation in our group. Applications of these devices in microfluidics include mixing of slow diffusing molecules and thermal control of biological reactions.

Coupling of discrete silicon elements to plastics is critical for achieving higher levels of integration with plastic microfluid devices. The approach in this paper describes the bonding of silicon chips with elastomeric polymer channels. We are also developing methods for marrying silicon chips containing active elements with microfluid networks fabricated in hard plastics.

Acknowledgement

This research is supported by the NIST Advanced Technology Program's DNA Tools for Diagnostics and by the NIST MicroAnalytical Laboratory Competence Building Project.

---

1. Burns, M.A., Johnson, B.N., Brahmasandra; S.N., Handique, K., Webster, J.R., Krishnan, M., Sammarco, T.S., Man, P.M., Jones, D., Heldsinger, D., Mastrangelo, C.H., Burke, D.T., "An Integrated Nanoliter DNA Analysis Device," *Science* 1998, *282*, 484-487.
2. McCormick, R.M.; Nelson, R.J.;Alonso-Amigo,M.G.; Benvegnu, D.J.; Hooper, H.H. "Microchannel Electrophoretic Separations of DNA in Injection-Molded Plastic Substrates," *Anal. Chem.,* 1997**,** *69*, 2626-2630.
3. Becker, H.; Dietz, W.; Dannberg, P. "Microfluidic Manifolds by Polymer Hot Embossing for m-TAS Applications," In *Micro Total Analysis Systems '98* Harrison, D.J., van den Berg, A., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1998; pp 253-256.
4. http://www.mosis.org/
5. N. H. Tea, V. Milanovic, C. Zincke, J. S. Suehle, M. Gaitan, M. E. Zaghloul, and J, Geist, "Hybrid Postprocessing Etching for CMOS Compatible MEMS," J. Electromechanical Systems, p. 363, December 1997.
6. L. Martynova, L. E. Locascio, M. Gaitan, G. W. Kramer, R. G. Chrisensen, and W. A. MacCrehan, "Fabrication of Plastic Microfluid Channels by Imprinting Methods," J. Analytical Chem, p. 4783, December 1997.
7. Duffy, D. C.; McDonald, J. C., Schueller, O. J. A.; and Whitesides, G. M., "Rapid Prototyping of Microfluidic Systems in Poly(dimethylsiloxane)," Anal. Chem., 70 (23), 4974 -4984, 1998.
8. Cavicchi, R., Poirier, G., Semancik, S., Suehle, J., and M. Gaitan, "Pulsed Desoprtion Kinetics Using Micromachined Arrays," American Vacuum Society, December 1993.
9. Parameswaran, M., Robinson, A.M., Blackburn, D.L, Gaitan, M., Geist, J., "Micromachined Thermal Radiation Emitter from a Commercial CMOS Process," *IEEE Electron Device Letters 12*, pp. 57-59, 1991.